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13. ABSTRACT *(Maximum 200 words)*
This final report summarizes the advances and developments associated with the ultra-high microwave device program at the University of California, Irvine. The program was a collaborative effort of researchers in the Department of Physics and Astronomy, and the Department of Electrical and Computer Engineering. We developed the means of fabricating and characterizing state of the art MBE grown semiconducting/ferromagnetic Fe hybrid structures. Chemical etching methods allowed us to create device structures, with microstrips of ferromagnetic Fe on the GaAs substrates. The coupling between microwaves propagating in the GaAs, and spin excitations in the Fe microstrip were measured and quantified. A high frequency notch filter was devised, which operated up to 32.5 GHz. Our theoretical effort developed quantitative theories of idealized device structures.

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Enclosure 1

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Multilayer Magnetic Material Structures for Ultrahigh Frequency Integrated Devices

Final Report

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I. Foreword:

In this document, we provide the Final Report on a project that involved the collaborative efforts of researchers in the Department of Physics and Astronomy, and the Department of Electrical and Computer Engineering, at the University of California, Irvine. The purpose of the effort was the development of a new generation of ultrahigh frequency microwave devices, using state-of-the-art semiconductor/ferromagnetic films hybrid structures. Excellent materials were prepared, utilizing a new molecular beam epitaxy system designed especially for this project, new microfabrication methods specific to the materials of interest were developed, and finally coupling between microwave signals guided in the semiconductor, and the spin degrees of freedom were demonstrated, up to frequencies in the range of 35 GHz. The device structure studied in this regard may be viewed as a prototype tunable notch filter.

II. Table of Contents:

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IV. The Purpose of the Effort; Results and Accomplishments:

A. The Problem Studied, and Motivation for the Effort:

There is a need for compact, high frequency microwave devices, which operate in the frequency range well above 20 GHz. Indeed, for a variety of reasons, it would be very exciting to see a new generation of devices which operate as high as 70-80 GHz. Many standard approaches fail to reach this frequency range. The effort summarized in this report had as its motivation the incorporation of very thin films of ferromagnetic Fe, and possibly magnetic multilayers which incorporate Fe, into microwave devices. The reason is that this material has resonant dynamic response to microwaves that may easily be tuned to the frequency region above 20 GHz through application of very modest magnetic fields. The resonant response has its origin in certain collective excitations of magnetic origin referred to commonly as spin waves. With free standing Fe films, modest magnetic fields compatible with device geometries may bring the resonances into the 35 GHz range, and the incorporation of Fe into certain multilayer structures referred to as exchange biased multilayers may allow one to go well beyond this frequency range.

In high frequency devices, metallic elements are commonly avoided, since they can introduce large ohmic losses that degrade device performance. The concept here is to fabricate hybrid structures formed from semiconductor/ferromagnetic metal film combinations. The semiconductor serves as a low loss microwave waveguide, while by virtue of the skin effect the microwave may couple in a resonant, tunable manner to the spin waves in the Fe film. Through manipulation of the spin wave, one envisions tunable notch filters by virtue of the selective absorption of the microwave; tuning over a wide range is possible through the fact that the spin wave frequency depends sensitively on magnetic field. In our effort, this was the central issue addressed, If sufficiently strong coupling could be demonstrated in the prototype notch filter, then other forms of signal processing are easily envisioned.

The effort was of a collaborative nature, between researchers in the Department of Physics and Astronomy, and the Department of Electrical and Computer Engineering, at the University of California, Irvine. In the Department of Physics and Astronomy, Prof. Hopster successfully developed the means of growing very high quality Fe films on GaAs substrates, through utilization of a molecular beam epitaxy (MBE) chamber, designed and developed for the ARO program. Prof. Mills, in combination with a consultant, Prof. R. E. Camley, developed a quantitative theory of the operation of model devices. In the Department of Electrical and Computer Engineering, Prof. C. C. Lee and graduate students designed new chemical etching techniques for the fabrication of appropriate microwave strip lines, which incorporated very thin (400A) Fe films, overcoated with a thick Ag film put in place to suppress the oxidation of the

Fe. Then the microwave device testing and characterization was carried out in the laboratory of Prof. C. S. Tsai, largely by a postdoctoral researcher, Dr. Jun Su, along with graduate students associated with the project.

B: Principal Results and Achievements:

This discussion will be divided into subsections, each covering the various phases of the program.

1. Materials Synthesis:

As mentioned above, the program required we develop the means of growing very high quality Fe films, on GaAs substrates. A critical issue is the quality of the interface region between the Fe and the GaAs; this must be as perfect as possible, on the atomic scale. The reason is that a critical device parameter is the ferromagnetic resonance linewidth realized in the hybrid structures. For the lines to be as narrow as possible (narrow lines lead to enhanced coupling between the spin waves and microwaves, according to theory), the quality of this interface must be as perfect as possible. This area of the program was developed and supervised by Prof. H. Hopster, in the Department of Physics and Astronomy.

In the early phase of the project, we utilized a large, ultra high vacuum MBE system which existed in the laboratory of Prof. Hopster at the outset of the program, for the growth of the samples. This allowed us to obtain very high quality materials early in the project. This UHV system has diverse sample characterization facilities built in. Among these are Auger electron spectroscopy (AES) for chemical surface analysis, and low energy electron diffraction (LEED). Both monitor surface quality and perfection on the atomic scale.

GaAs substrates can be introduced through a load-lock and they were then cleaned in UHV by heating to the range of 550-580C. They were then subjected to mild sputtering for a few minutes, using 500eV Ne with a current of 10 micro amperes. Optimum growth temperatures were found to be in the range of 150-170 C, with a deposition rate of a few atomic layers per minute. The pressure as the deposition process proceeded was in the range of 10^{-10} Torr. We determined that under these conditions, we could realize very high quality Fe films. The final Fe thickness for most samples was in the 40-50 nm range, and the films were capped in the UHV environment with very thin (typically 5 nm) Au or Ag layers to protect them from oxidation.

The films were then characterized ex-situ by magnetic measurements, using the magnetooptic Kerr effect (MOKE). We consistently obtained remarkably square hysteresis loops, with very low coercive fields. This is consistent with Fe films of single crystal character, that were both uniform in character and also single crystals. In addition, the films were characterized by ferromagnetic resonance (FMR) using a

commercial ESR apparatus at 9.6 GHz available in the Chemistry Department, at UC Irvine. We consistently found linewidths below 30 gauss. These very small linewidths, in combination with the excellent square hysteresis loops convinced us we had indeed succeeded in growing excellent films, whose quality is truly state of the art.

We then designed and constructed a new, small UHV chamber fully dedicated to the ARO effort. This system offered the same growth conditions as the large chamber used initially, though the sample characterization facilities (AES, LEED) present in the large chamber were not incorporated into the small system. As a consequence, we would utilize the large chamber on occasion, to check continued consistency of sample quality. The small chamber allowed us to produce a very large number of samples, once the optimum "growth recipe" was determined through use of the large system. The new system was designed and tested in the laboratory of Prof. Hopster, and it was then physically transferred to the laboratories in the Department of Electrical and Computer Engineering for routine sample production. The samples produced by this facility were monitored for quality through FMR studies,, using the facility in the Department of Chemistry.

In the 1997-1998 academic year, a UHV atomic resolution scanning tunneling microscope was purchased from Omicron, by use of funds supplied by a DOD-University Research Instrumentation Grant. The instrument was delivered in early 1999. It has now been integrated within the large MBE chamber, thus enhancing our sample characterization abilities very substantially. It should be remarked that the installation of this device required major changed in the design of sample holders, and sample transfer arms, to make our existing system compatible with the STM sample and tip holders. This has recently been completed, and we have been able to obtain atomic resolution test images on this microscope, under UHV conditions.

2. Device Fabrication Techniques and the Microwave Measurement Facility:

This aspect of the project was developed and pursued in the laboratories of Prof. C.S. Tsai, and Prof. C. C. Lee, of the Department of Electrical and Computer Engineering.

A first step was the establishment of microwave measurement capabilities up to the 26 GHz range. This was accomplished with equipment purchased with $250,000 in matching funds, provided by UC Irvine, at the beginning of the program. Key device parameters that can be and were measured with this facility include reflection coefficients, transmission coefficients, coupling parameters, and scattering parameters in the frequency domain up to 26 GHz. In the frequency domain up to 26 GHz, we realized impulse reflection response in the time domain, with rise times less than 18 picoseconds. This measurement capability was further

partially expanded to 50 GHz using equipment purchased with funds received from the 1997-1998 DOD University Research Instrumentation Program, combined with matching funds provided by the UCI campus. It is the case that additional components remain to be acquired, for this extension to be complete.

In a parallel effort, methods were developed for successfully fabricating microstrips on semi-insulating GaAs substrates. The microwave facilities described in the previous paragraph were then employed to study and characterize their performance.

In Fig. 1, we show the measured insertion loss, and return loss of a 100 micron wide microstrip built on a 150 micron thick GaAs substrate. The line length for this particular sample was 8 mm, and the line was designed to have a characteristic impedance of 50 ohms to match that of coaxial connectors, coaxial cables, and the sweep generator. The circuit being measured includes the microstrip line and two coaxial connectors. One can see that the insertion loss is within 2.5 dB for frequencies up to 29 GHz. We regard this as an excellent achievement. Above this frequency, we see large oscillations. This is evidently caused by multiple reflection of signals in the line, with origin in the mismatch of electric field distribution in the line, and that of the coaxial connector. Even though the microstrip line and the coaxial connector each have an impedance of 50 ohms, a good impedance match along does not guarantee also a match of the electric field distributions. This mismatch in the field distributions becomes more severe at higher frequency, causing both the higher reflectivity and also possibly the oscillatory response. Further theoretical study and more experiments would have been required in the program, to achieve flat response to frequencies as high as 50 GHz. It should be noted also that at such high frequencies, the microstrip line supports not only the fundamental TM mode, but higher modes as well. In the literature, one finds virtually no theoretical work that addresses such issues, and their consequences. It would be most interesting indeed, to see such questions addressed. This will be essential for proper design of devices that operate in the frequency range well above 30 GHz.

The device fabrication methods we developed are described in the previous section. After the samples were removed from the MBE chamber, two small pieces were cleaved off the sample, one for the FMR measurement as a means of characterizing quality, and one for the "flip chip" device oriented studies in the microwave laboratory. The main part of the sample was retained for further device study and research. Chemical processing methods were then utilized to fabricate the integrated type microwave bandstop (notch) filters, the prototype device studied on our program.

The device fabricated in this manner was cleaved to appropriate size and placed on a microwave test fixture. Then 50 GHz coaxial connectors

were mounted and connected onto the device for measurement. The results of these measurements are summarized in the next subsection.

3. Realization of Wideband Tunable Microwave Devices:

As we shall see in this section, we realized a major initial goal of the project. This is the realization of prototype tunable microstrip based notch filters, which operated up to 35 GHz, utilizing only modest applied magnetic biasing fields. We begin with some background.

As noted in the opening remarks, it is the coupling between microwaves which propagate within the GaAs film, here regarded as simply a dielectric waveguide, and the collective spin excitations in the Fe films that provide the mechanism for the attenuation necessary for the operation of the notch filter. The fact that the microwave field penetrates into the Fe film by virtue of the skin effect is the origin of the coupling. The microwave comes into resonance with the spin wave in the Fe film when its frequency equals

$$f_{res} = \gamma[(H_0 + H_{an})(H_0 + H_{an} + 4\pi M_S)]^{1/2} \qquad (1)$$

where γ is the gyromagnetic ratio, H_0 the strength of an applied biasing field, H_{an} the anisotropy field (the expression assumes the magnetization of the film is aligned along the easy axis), and M_S is the magnetization of the film. For the commonly used microwave device material YIG, the anisotropy field is roughly 100Oe, $4\pi M_S$ is 1750 Oe, so we require a 4150 Oe external field to realize a resonance frequency of only 14 GHz. In contrast, for Fe, the working medium of the prototype device developed in our project, $4\pi M_S$ is 22 kOe, the anisotropy field is around 550 gauss, so the corresponding resonance frequency is 32 GHz. This example shows the virtue of employing Fe films rather than YIG films as the working media.

In Fig. 2, we show the waveguide layer structure developed and studied in this program. After the Fe film was grown as described above, and the Ag or Au capping layer was added, a sequence of chemical etching processes were developed which allowed us to produce a microstrip 6 mm in length, with a very uniform width of 80 microns. This formed a microstrip line with a 50 ohm characteristic impedance. Also, for preliminary testing, simple flip chip bandstop filters were constructed as well. On our flip chip samples, a 50 ohm microstrip transmission line was formed on a separate 350 micron thick substrate. Our measured transmission characteristics for the microstrip line for a quasi TEM mode extend up to a frequency as high as 35 GHz. An Fe/GaAs sample such as that used in the integrated type filter was flipped and laid upon the GaAs based microstrip transmission line. Either type of finished sample was than inserted in a magnetic circuit that could provide a large tuning range in amplitude for the bias magnetic field. Its direction in the film plane could be altered as well.

As noted above, the operating principle is that an incident microwave which propagates along the GaAs based microstrip line is coupled into the Fe film in either type of filter to excite the FMR spin wave mode; this leads to resonance absorption of power. The resonance frequency is readily tuned by varying the applied biasing field, as illustrated by Eq. (1).

In Fig. (3) through Fig. (7), we summarize our principal results. We see we have realized tunability, with substantial absorption of the microwave field, to frequencies almost up to 35 GHz. We find that although the flip chip type filters provide a lower level of signal absorption and lack the robustness that is inherent in the integrated type filters, the simple surface contact involved has facilitated a quick and effective means for selection of the Fe/GaAs samples. We have consistently found that the same Fe/GaAs sample that provides good filtering characteristics in the flip chip type device does so also in the integrated chip type device. Thus, selection of the samples can be quickly made prior to the chemical processing steps required in fabrication of the integrated type devices.

In conclusion, a major goal of the project has been realized through the results just described. We have achieved the realization of tunable wideband microwave band stop filters; these have been constructed and tested using ultrathin Fe/GaAs waveguide layer structures. Transmission characteristics of the filters are evaluated using the flip chip and integration techniques. A frequency tuning range between 10.7 to 32.5GHz has been accomplished in the integrated type filters. The experimental results are in excellent agreement with theoretical predictions for the resonance frequency, both for the case where the field is applied along the easy, and also when it is applied along the hard axis of the film. We remark that the theory developed in the course of the project also predicts the strength of the coupling, as evidenced by the depth of the attenuation dips. The data are in excellent accord with theory in this regard.

4. Theoretical Modeling:

The purpose of the theoretical program was to address both fundamental issues of physics that will affect the potential characteristics of the high frequency devices explored in the experimental phase of the proposed program, and also to analyze specific device geometries to assess the performance that might be realized at least in idealized structures. Also, such studies outlined how structures should be fabricated, so optimum performance may be realized. It should be remarked that the studies described below were carried out by Prof. Mills, in the Department of Physics and Astronomy. Prof. R. E. Camley, from the University of Colorado in Colorado Springs functioned as a consultant to the project. Important contributions came from his involvement, it should be remarked.

As we have seen above, in the laboratory phase of the program, the propagation of microwaves in a GaAs dielectric substrate on which a

ferromagnetic Fe film was deposited were studied. Thus, it became of central importance to understand how one might achieve maximal coupling of the microwave signal to spin waves in the Fe film, and how this might be optimized by alterations in the device microstructure.

We developed a quantitative theory of a model geometry, which consisted of a GaAs film, with a ferrromagnetic Fe film deposited on both its top and bottom surface. In the actual devices, of course the Fe film was present only on one surface and a grounding plane on the second, but an elementary argument tells relates the theoretical model to the actual device geometry: the theory provides results appropriate to a device whose GaAs film thickness is just half of that in the model study. We also explored, in our theory, alternate structures which employed diverse magnetic multilayers. This led us to propose a new and innovative structure within which a very high frequency (roughly 70 GHz) band pass filter can be realized, at least in principle.

Our theory, applied to the Fe/GaAs structure, yielded important conclusions that can guide device design. First, the attenuation realized in a prototype notch filter varies in strength inversely with the thickness of the GaAs film itself. Thus, to realize strong coupling, one should synthesize structures with very thin waveguiding films. This suggests, for example, one might grow very thin GaAs films on top of thick substrates that serve only a support function. We also found that the Ag cap layer plays an unsuspected role: it suppresses the ohmic dissipation off resonance created by the conducting character of the Fe film. This, and other quantitative aspects central to the device of a very high frequency notch filter, are discussed in the publication by Camley and Mills, in the publication list cited below.

A most interesting phenomenon was revealed by our theoretical studies. First of all, many years ago, it was discovered that conducting, ferromagnetic films display a most remarkable phenomenon, called " anti resonance" by its discoverers. Consider the microwave transmissivity of a metallic ferromagnetic films, whose thickness is comparable too or somewhat larger than its skin depth. The transmissivity will clearly be very small indeed; such a material reflects virtually 100% of the microwave radiation that strikes one of its surfaces. But there is a characteristic frequency well above the FMR frequency where, by virtue of coupling between microwaves and spin motions in the ferromagnet, the skin depth becomes very large indeed. The film exhibits a transmission resonance in this regime. In essence, the skin depth opens up.

We predict that one may synthesize a metal rich multilayer structure, with dielectric spacers between adjacent metallic ferromagnetic films such as Fe. While a TEM mode may propagate in such a structure by virtue of the dielectric films, its propagation length is very short indeed, by virtue of the very strong ohmic damping. However, at the characteristic frequency described in the previous paragraph, the structure "opens up",

and by virtue of the anti resonance phenomenon, the propagation will be very long in a limited frequency window. Thus, the structure will function as a very high frequency band pass filter. For Fe, the frequency lies in the range of 70 GHz, and this may be tuned through application of a biasing magnetic field over an appreciable range. By using ferromagnetic alloy films, this anti resonance may be moved down in frequency, and exchange biased structures may allow it to be shifted upward, It would be most intriguing to see a search for this transmission window, in samples such as we proposed.

We also developed a quantitative theory of the ferromagnetic resonance response of thin conducting ferromagnetic films. This allows for "spin pinning" at each film surface, and in the program we developed we allow this to be different on each surface. The magnetic field could be oriented in plane in any direction, so we can explore sensitivity of the FMR response to misalignment of the field with the easy or the hard axis, in plane. The theory provided a remarkably quantitative account of the data taken at UC Irvine on the 9.6 GHz spectrometer here.

Also, Prof. B. Heinrich at Simon Fraser University also kindly performed FMR measurements on some of our samples, at 24 and 36 GHz. This provided us with much needed linewidth data at these important frequencies. More importantly, Prof. Heinrich observed a hitherto unobserved low field satellite to the main FMR line. This has its origin in the first "standing spin wave" resonance of the film. This mode has never been seen before in a thin film; it appears in his spectra, because our films in fact are much thicker than the ultrathin MBE grown Fe films studied recently in numerous laboratories. Application of our theory to the samples, which had Fe films grown quite directly on the GaAs, showed that one requires very, very strong "spin pinning" at the Fe/GaAs interface to produce a satellite line at the correct resonance field and of the correct intensity. The presence of this very strong spin pinning is very unfavorable for devices such as the program explored. It can be removed, it turns out, by first growing a few nanometers of Ag on the GaAs surface, then depositing the Fe film on top of the Ag film. In the later part of the program, all of our samples incorporated a Ag buffer layer.

The theory effort provided very explicit guidance to both the materials synthesis and device design stages of the effort, as one can see from the above remarks.

C. List of Publications:

The following publications emerged from our effort:

1. R. E. Camley and D. L. Mills, "Theory of Microwave Propagation in Dielectric/Magnetic Film Multilayer Structures", Journal of Applied Physics **82**, 3058(1997).

2. C. S. Tsai, Jun Su and C. C. Lee, "Wideband Electronically Tunable Microwave Bandstop Filters Using Fe Film/GaAs Waveguide Structures", IEEE Transactions on Magnetics, **35** , 3178(1999).

3. C. S. Tsai and Jun Su, "A Wideband Electronically Tunable Magnetostatic Wave Notch Filter in YIG-GaAs Waveguide Structures",IEEE Ultrasonics Symposium Proceedings, edited by S. C. schneider, M. Levy and B. R. Avoy, **1** ,123(1998).

4. C. S. Tsai and Jun Su, "A Wideband Electronically Tunable Microwave Notch Filter in Yttrium Iron Garnet-Gallium Arsenide Material Structures", Applied Physics Letters **74**, 2079(1999).

5. C. S. Tsai, C. C. Lee, J. Su, W. So, W. Wu, H. J. Yoo, G. Giergel, H. Hopster and D. L. Mills, "Wideband Electronically Tunable Microwave Band Stop Filters Using Iron Gallium Arsenide Waveguide Layer Structures", Applied Physics Letters (submitted).

D. List of All Participating Scientific Personnel:

Prof. C. S. Tsai, Co-Principal Investigator (Dept, of Electrical and Computer Engineering)

Prof. D. L. Mills, Co-Principal Investigator (Dept. of Physics and Astronomy)

Prof. C. C. Lee, Faculty Collaborator (Dept. of Electrical and Computer Engineering)

Prof. H. Hopster, Faculty Collaborator (Dept. of Physics and Astronomy)

Dr. Jerzy Giergel, Visiting Associate Researcher (Dept. of Physics and Astronomy)

Dr. Jun Su, Postdoctoral Researcher (Dept. of Electrical and Computer Engineering)

Wei Wu, Graduate Student Researcher (Dept. of Electrical and Computer Engineering)

William So, Graduate Student Researgher (Dept. of Electrical and Computer Engineering)

Ricky Chang, Graduate Student Researcher (Dept. of Electrical and Computer Engineering)

Wende Zuo, Graduate Student Researcher (Dept. of Electrical and Computer Engineering)

Jae Yoo, Graduate Student Researcher (Dept. of Electrical and Computer Engineering)

Yinglei Yu, Graduate Student Researcher (Dept. of Electrical and Computer Engineering)

V. Report of Inventions:

There were no inventions or patents granted during the course of this project.

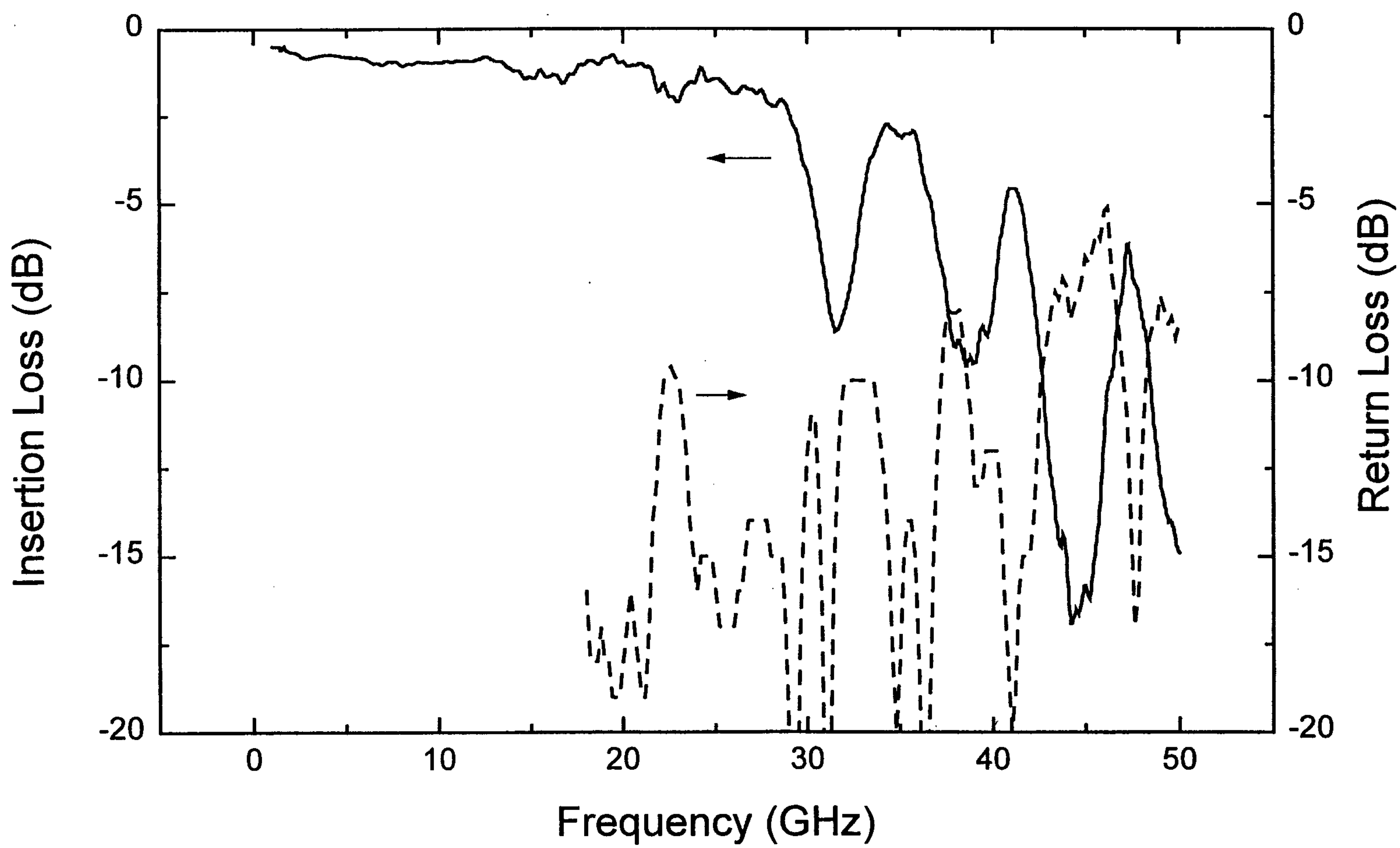

Fig. 1 Measured Insertion Loss and Return Loss of a 100 μm Wide Microstrip Line on a 150 μm Thick GaAs Substrate

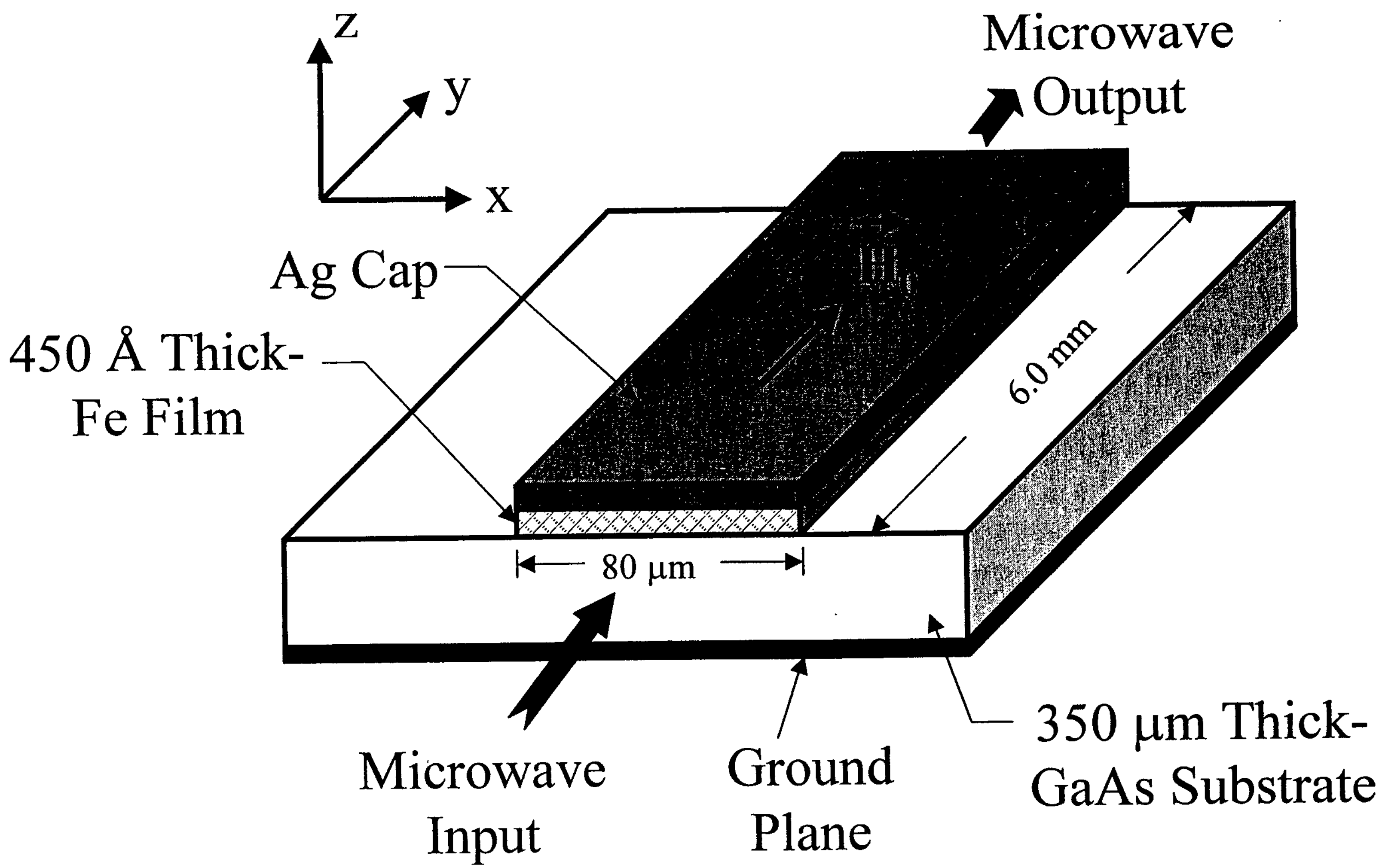

Fig. 2 An Integrated Type Tunable Microwave Band-Stop Filter Using Ultrathin Iron-Gallium Arsenide Waveguide Layer Structure

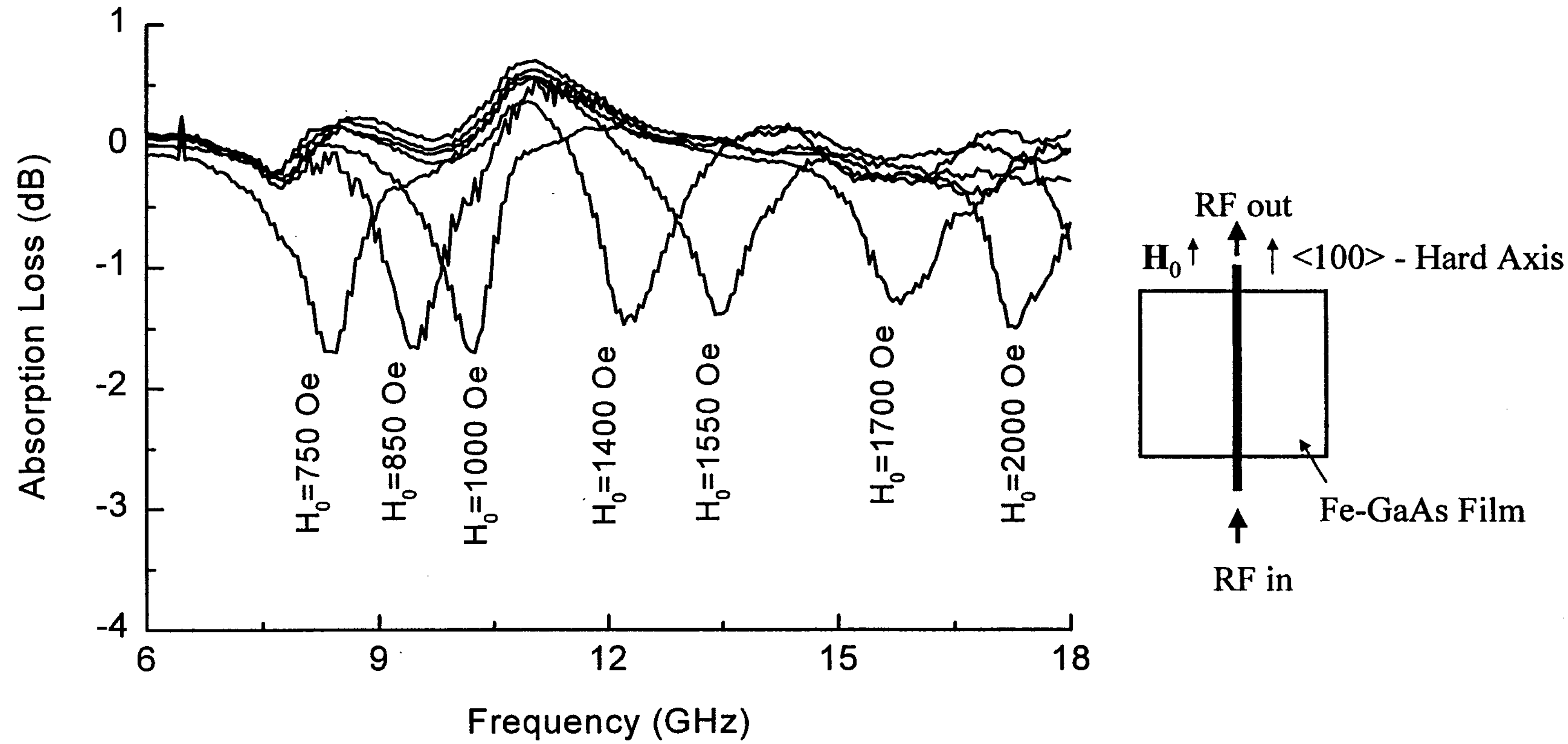

Fig. 3 Tuning of Peak absorption Carrier Frequency of the Integrated Type Filter When the External Magnetic Field is Applied and Varied along the Hard Axis of the Fe Film.

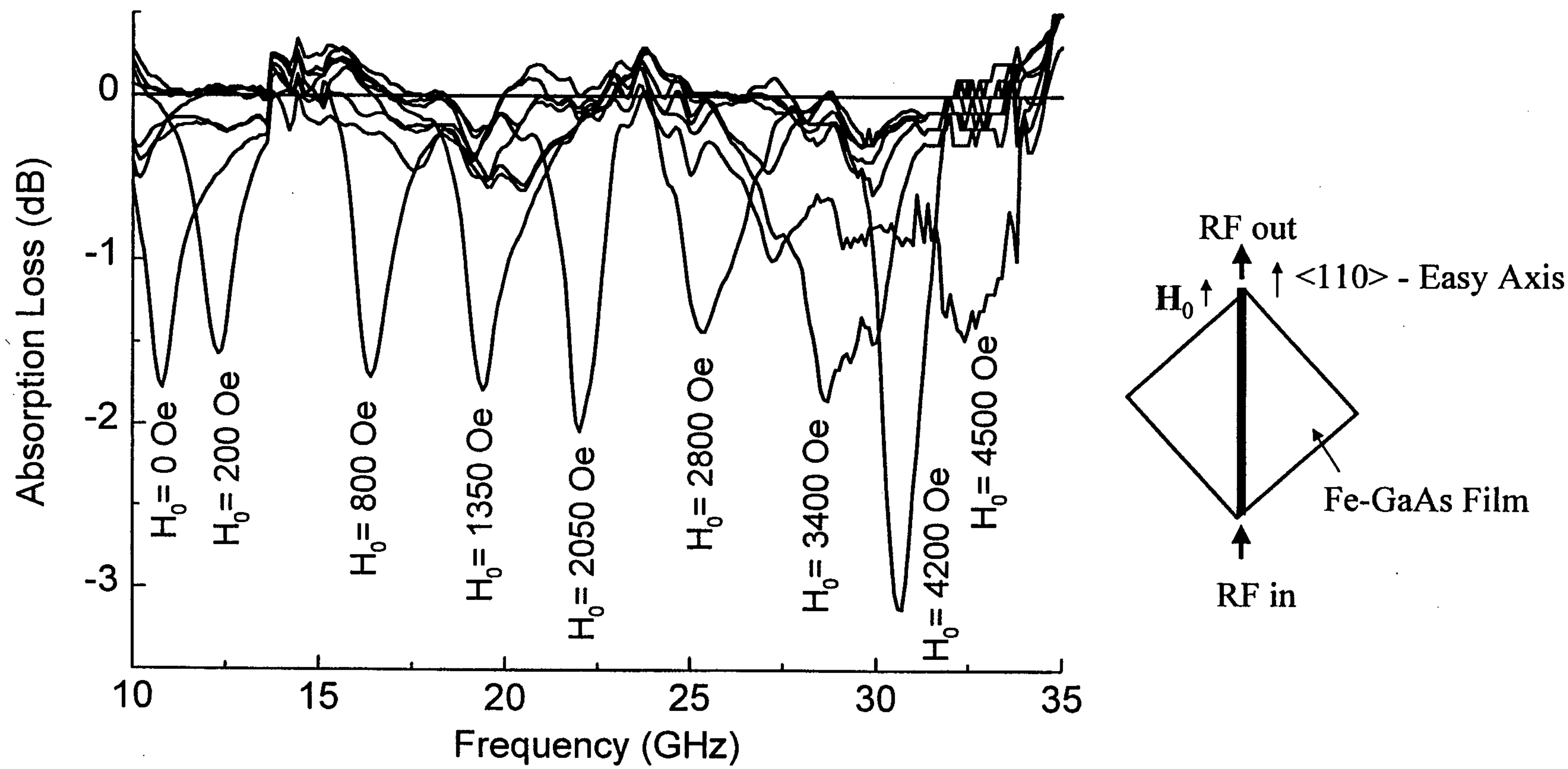

Fig. 4 Tuning of Peak absorption Carrier Frequency of the Integrated Type Filter When the External Magnetic Field is Applied and varied along the Easy Axis of the Fe Film.

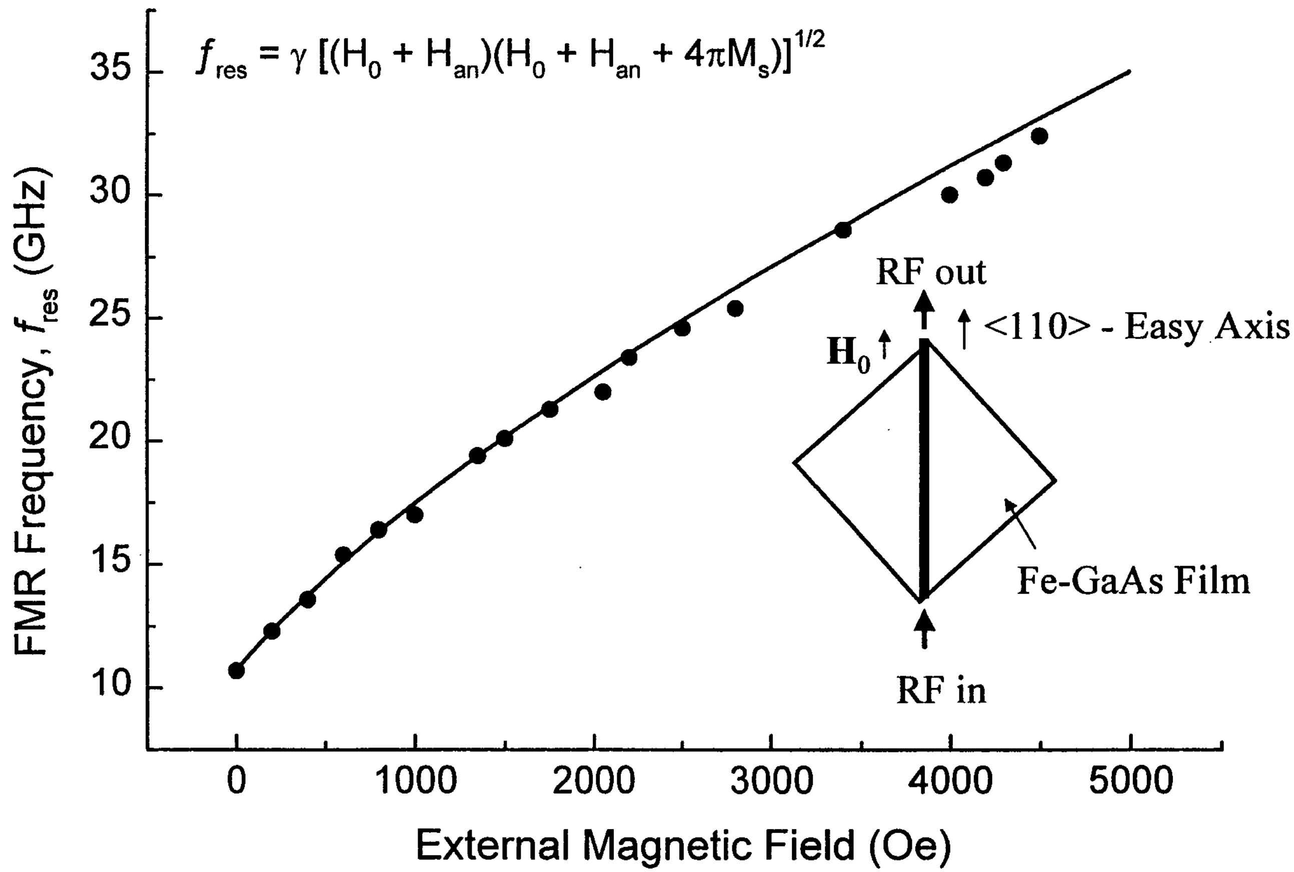

Fig. 5 Comparison of Calculated and Measured Peak Absorption versus Bias Magnetic Field while the Magnetic Field is Applied and Varied along the Easy Axis of the Fe Film

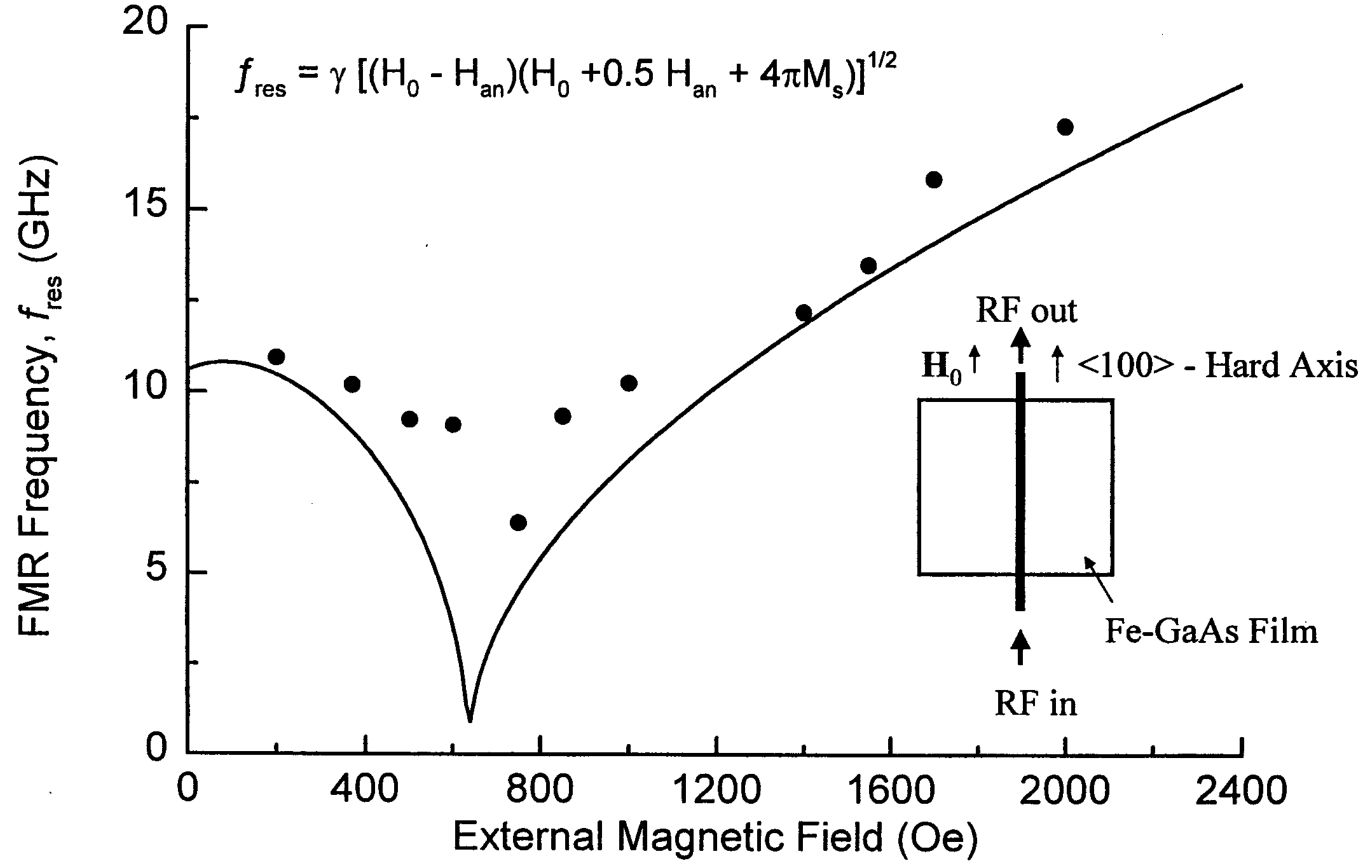

Fig. 6 Comparison of Calculated and Measured Peak Absorption versus Bias Magnetic Field while the Magnetic Field is Applied and Varied along the Hard Axis of the Fe Film

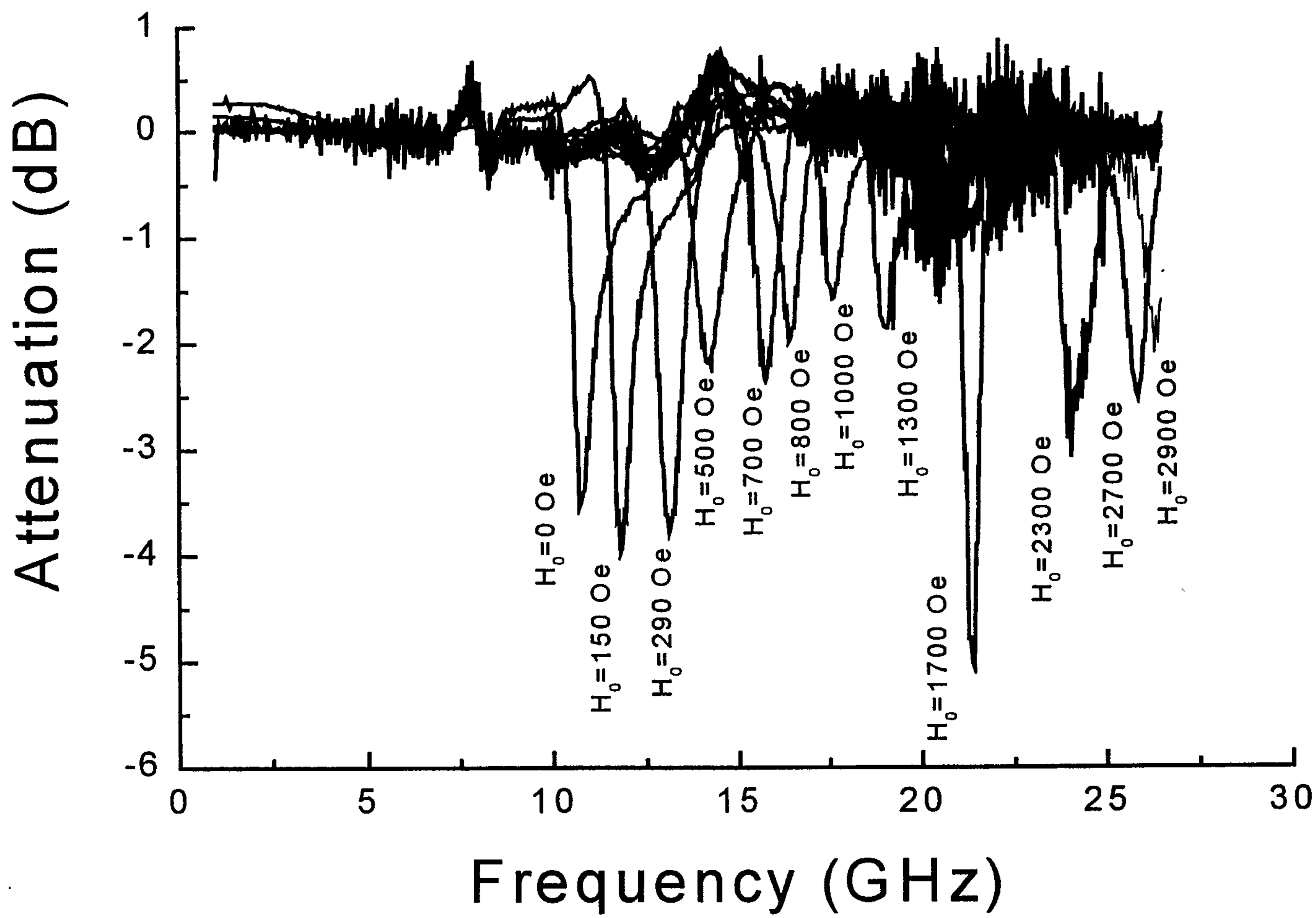

Fig. 7 Transmission Response of the Fe-GaAs Filter (H_0//Easy Axis)